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SUMMARY OF COMPARISON OF ENGINEERING PROPERTIES OF SELECTED TEMPERATE AND TROPICAL SURFACE SOILS

by

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U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

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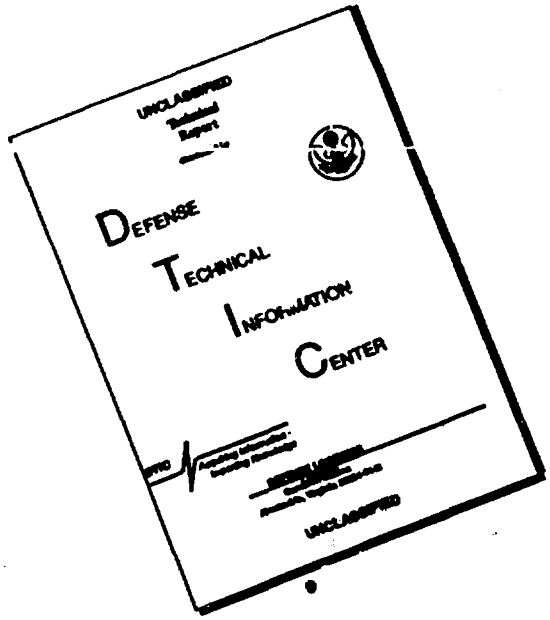

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FOREWORD

This paper summarizes a report, "Comparison of Engineering Properties of Selected Temperate and Tropical Surface Soils," published by the U. S. Army Engineer Waterways Experiment Station (WES) in June 1966. The paper was approved for open publication by the Directorate of Security Review (OASD-PA), Department of Defense, and was presented at the Second International Conference on the Mechanics of Soil-Vehicle Systems in Quebec, Quebec, Canada, on 2[illegible] August 1966, and at the annual meeting of the Geological Society of America in New Orleans, Louisiana, on 22 November 1967.

The study was performed by personnel of the Mobility and Environmental Division, WES during the period January 1963 to February 1965. It constitutes a portion of the Mobility Environmental Research Study, sponsored by the Office, Secretary of Defense, Advanced Research Projects Agency, Directorate of Remote Area Conflict, for which WES is the prime contractor and the U. S. Army Materiel Command is the service agent.

Directors of the WES during conduct of this study and preparation of this report were Colonel Alex G. Sutton, Jr., CE, and Colonel John R. Oswalt, Jr., CE. Technical Director was Mr. J. B. Tiffany.

SUMMARY OF

COMPARISON OF ENGINEERING PROPERTIES OF SELECTED TEMPERATE AND TROPICAL SURFACE SOILS

by

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Abstract

Field and laboratory tests were conducted on 11 fine-grained soils from the temperate climate of the United States and 17 fine-grained soils from the tropical climates of Puerto Rico, Panama Canal Zone, Hawaii, and Thailand to determine trafficability of the soils and other engineering properties. Soils were collected from the 6- to 12-in. layer for a wide range of parent materials. Temperate and tropical soils of each parent material were selected on the basis of their similarity in the Unified Soil Classification System and topographic position.

A comparison of physical, mineralogical, and chemical properties, and results of standard and special engineering tests indicate, with few exceptions, no significant differences between temperate and tropical soils from a similar parent material.

It is concluded that temperate and tropical soils of similar parent materials and Atterberg limits generally have other engineering properties that are similar and behave similarly when subjected to standard and special engineering laboratory tests. Differences in behavior between soils from each of the climates can be associated with differences in Atterberg limits.

SUMMARY OF
COMPARISON OF ENGINEERING PROPERTIES OF SELECTED TEMPERATE AND TROPICAL SURFACE SOILS

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Introduction

An appreciable amount of knowledge has been obtained on the physical characteristics of surface soils of temperate climates. This information has been used to identify the engineering properties of given soil types and to develop techniques for predicting those characteristics in soils that cannot be examined directly. However, relatively little work of this nature has been conducted on soils of tropical climates. A study comparing the properties of temperate and tropical soils would have a broad utility. For example, if the soils are highly analogous, convenient temperate climate areas that are representative of tropical conditions could be selected for testing soil-vehicle systems. Furthermore, a comparative study would provide detailed data on the relations among characteristic physical properties of various soil types and of soils of similar parent materials.

This paper summarizes a study of the engineering properties of 28 soils conducted to determine the degree of analogy between soils from temperate and tropical climates. The study shows the relations among physical properties of the soils and the horizontal variability of physical properties of temperate and tropical soils in situ. A detailed report on the study has been published by the U. S. Army Engineer Waterways Experiment Station (WES).[1**]

Field and laboratory tests were conducted on 11 temperate and 17 tropical soils. The 6- to 12-in. soil layer was selected for testing because it is considered to be the critical layer in determination of "go"

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**Raised numbers refer to similarly numbered items in References at end of text.

or "no go" performance on a multiple pass basis for most standard military vehicles. At each site the field data and soil samples were collected on one day, or occasionally on two days, at the end of the wet season from three sites in Oregon, four in Mississippi, one in North Carolina, one in South Carolina, one in Georgia, and one in Alabama in the United States for the temperate soils and from three sites in Hawaii, seven in Puerto Rico, two in the Panama Canal Zone, and five in Thailand for the tropical soils. The location and parent material of each soil are shown in table ~~plate~~ 1.

The parent materials and the number of temperate and tropical soils studied in each are shown in the following tabulation.

Parent Material	No. of Temperate Soils	No. of Tropical Soils
Basic igneous rock	3	4
Acidic igneous rock	1	1
Volcanic ash	1	1
Limestone	1	2
Old water-deposited material	2	4
Recent alluvial clay	2	2
Recent alluvial silt	1	3

Soils of each category generally were of the same soil type, as classified according to the Unified Soil Classification System, and generally were located at the same topographic position.

Field Tests

Twenty 1-ft-sq plots, 3 ft apart, were established at 9- by 12-ft sites. Soil strength (cone index and remolding index) was measured in each plot, and samples were taken for determination of moisture content, dry density, and Atterberg limits. The data were used in the study of horizontal variability of the soil. Also, large bulk samples were collected in each of the 20 plots and composited for use in other laboratory tests.

Laboratory Tests

The flow diagram in fig. 1 shows the tests performed on the samples, he procedures for processing the soil, the laboratory in which the tests ere conducted, an the approximate weight of the sample reserved for each est or series of tests. Tests were conducted in accordance with standard r acceptable modified engineering procedures. From 6 to 11 samples from ch soil were prepared at specific moisture contents ranging from one oviding a cone index less than 20 to one slightly less than optimum (for compaction effort used). The sample at each moisture content was com- ted with an energy equivalent to the standard American Association of ite Highway Officials (AASHO) compaction effort in a mold 15 in. in meter and 7 in. high.

The same series of tests was performed on each soil: A represen- ive sample was obtained from each mold for determination of moisture tent and dry density, and cone index and CBR tests were performed in the d; unconfined compression, sheargraph, and rubber-wheel friction tests e performed on specimens carefully cut from each mold consolidation, meability, and drained direct shear tests were conducted on specimens tained from the mold that had been prepared at optimum moisture content; d tests to determine the moisture content of the soil at tensions of 0 (saturation) and 0.06 atmosphere were conducted on cores obtained from molds prepared at field density and lowest density (highest moisture content) of the soil. Other tests conducted on the composite sample of each soil included a determination of moisture content at 0.33-, 3-, and 15-atmosphere tension, grain-size distribution (mechanical analysis), Atterberg limits, specific gravity, percent organic matter, soluble salts content, and acidity (pH), and a mineralogical and chemical analysis. Soil property data are shown in table 1.

Test Results

Horizontal variation of soil properties measured at site

The standard deviations and coefficients of variation of the soil properties of each of the 11 temperate and the 17 tropical soils were determined on the basis of 20 observations at each site. The means of these statistical parameters are shown below.

	Mean Standard Deviation		Mean Coefficient of Variation, %	
	Temperate Soils	Tropical Soils	Temperate Soils	Tropical Soils
Cone index	37	48	18	18
Remolding index	0.14	0.14	16	16
Rating cone index	48	56	24	25
Moisture content, %	3.3	2.4	7	6
Dry density, lb/cu ft	4.2	4.8	5	6
Liquid limit	5	5	6	6
Plastic limit	2	2	6	4
Plasticity index	4	4	13	11

An evaluation of these data shows a similar degree of horizontal variation of the soil properties for temperate and tropical soils. For tropical soils the standard deviations of cone index, rating cone index, and dry density were slightly higher and the standard deviation of moisture content was slightly lower than those of temperate soils. However, the coefficients of variation were about the same, indicating that the small differences in standard deviation can be attributed to differences in the average mean of these properties.

Specific gravity-
plasticity index relations

Relations between specific gravity and plasticity index were determined for residual soils developed from igneous rock, volcanic ash, and limestone parent materials, and for soils developed from old and recent water-deposited material. The data for residual soils show that the specific gravities decreased with an increase in plasticity index and that the tropical soils had higher specific gravities than the temperate soils at a given plasticity index. The specific gravities of the water-deposited soils do not appear to be related to the plasticity index, nor do there appear to be any meaningful differences in values of specific gravity between temperate and tropical soils of this type.

Organic matter content

A comparison was made of the percentages of organic matter content for temperate and tropical soils of the same parent materials. The percentages of organic matter for the tropical soils derived from basic and acidic igneous rock and limestone generally were greater than those of the same types of temperate soils. However, no obvious differences are indicated between temperate and tropical soils derived from water-deposited materials (old water-deposited materials and recent alluvial clay and silt).

Soluble salts content

Electrical conductivity, which is a measure of the soluble salts content, was not consistently different in temperate and tropical soils of the same parent materials. The electrical conductivities were somewhat less for tropical than for temperate soils from volcanic ash, greater for tropical soils from old water-deposited material, and rather inconsistent for soils from recent alluvial clay and silt.

Acidity

A comparison of pH for temperate and tropical soils showed no pattern of differences. Except for the slight alkalinity of one temperate and one tropical soil, the soils were all acidic.

Moisture-tension relations

The relations between moisture content at 0- and at 0.06-atmosphere tension, density, and percent saturation for soil samples compacted in the laboratory to approximately field-density condition were well defined. The degree of saturation of soil samples compacted to about field density usually ranged from 90 to 100 percent. Highest saturations were indicated for the low-density, high-moisture-content soils that were chiefly from tropical climates. The relation between moisture-tension and Atterberg limits data for each soil showed the moisture contents at 0- to 0.06-atmosphere tension close to each other and usually falling between the plastic and liquid limits. The moisture contents at 0.33- and 3-atmosphere tensions were higher or lower than the plastic limit, and the moisture content at 15-atmosphere tension was lower than the plastic limit and equal to approximately 0.4 of the liquid limit of the soil. These relations applied equally to temperate and tropical soils.

Mineralogical and chemical composition

The data on mineralogy and chemistry indicated no distinct mineral or chemical, or combination thereof, that could be used to distinguish temperate from tropical soils. The iron contents of two tropical soils were appreciably higher than those of the other soils; however, other tropical soils had low iron contents, and it is very probable that there are soils in the United States with high iron contents.

Strength and density versus moisture content for compacted soil

Curves to show the relations between moisture content and density, cone index, CBR, and unconfined compressive strength, respectively, were drawn for each soil. A comparison of the data showed no meaningful differences in the curves for temperate and tropical soils, i.e. the change of dry density and of each strength parameter, respectively, per unit change in moisture content was approximately the same.

Relations between strength parameters

The relation between cone index and CBR for each soil is shown on logarithmic plots in fig. 2. The soils were grouped by climate, and an average line of best fit for all soils of each climate is shown. A similar set of relations between cone index and unconfined compressive strength is presented in fig. 3. The relation for each soil was determined from data obtained in laboratory tests at optimum and wetter-than-optimum moisture contents. The average lines for each set of relations have approximately the same slope and intercept, indicating that there was no meaningful difference in the relations for temperate and tropical soils. At a CBR value of 1, the cone indexes for temperate soils ranged from 34 to 82 and averaged 53, and those for tropical soils ranged from 35 to 98 and averaged 54 (fig. 2). At 10-psi unconfined compressive strength, the cone indexes ranged from 63 to 100 and averaged 78 for the temperate soils, and ranged from 70 to 116 and averaged 86 for the tropical soils.

Relations at optimum moisture content

Relations between optimum moisture content and maximum dry density, liquid limit, and plastic limit, respectively, for all soils were found to be highly correlative. The equation, correlation coefficient (r), and standard deviation from the regression ($Sy \cdot x$) for the relation between optimum moisture content (W_o) versus liquid limit (LL) and plastic limit (PL), respectively, are as follows:

$$W_o = 0.41\ (LL) + 5.9;\ r = 0.85^{**\dagger};\ Sy \cdot x = \pm 5.8\%$$

$$W_o = 1.74\ (PL)^{0.82};\ r = 0.90^{**\dagger};\ Sy \cdot x = +5.3,\ -4.5\%$$

In each relation, a projected line of best fit for temperate soils would have approximately the same slope and intercept as one for tropical soils; therefore, it is concluded that the relations for temperate and tropical soils were not different. The range and mean values of cone index, CBR, and unconfined compressive strength at optimum moisture content for temperate and tropical soils, respectively, were as follows:

Soils	Cone Index		CBR		Unconfined Compressive Strength, psi	
	Range	Mean	Range	Mean	Range	Mean
Temperate	130-381	212	3.0-9.0	5.2	15.0-34.8	25.8
Tropical	147-415	250	2.5-7.5	5.6	15.9-32.4	26.0

These data show a range of values for each strength parameter that was approximately the same for temperate and tropical soils. The mean values for the tropical soils were slightly greater than those for the temperate soils; however, it is not believed that these differences are meaningful.

Rubber-wheel friction test

Data for the rubber-wheel friction test were obtained from a friction test machine (see fig. 4) designed and built by the WES. A smooth, hard-rubber wheel 12 in. in diameter by 2 in. wide rests on the surface of a soil sample under a constant load. The torque, angular displacement, and

† In this paper a double asterisk (**) indicates significance at the 1% level; a single asterisk (*) indicates significance at the 5% level.

sinkage of the wheel in the soil are measured electrically during two slow revolutions of the wheel. Wheel loads of 5, 20, and 35 lb were used on both as-built (unflooded) samples of soil and similar samples that had been flooded with water just prior to testing. The contact pressure (p) and traction index (TI), an index of the shear strength of the soil measured by the rotating wheel, were computed for each test as follows:

$$P \text{ (psi)} = \frac{\text{load (lb)}}{\text{contact area (sq in.)}}$$

$$TI \text{ (psi)} = \frac{\text{torque (in.-lb)}}{\text{radius of wheel (in.)} \times \text{contact area (sq in.)}}$$

Relations were developed between traction index and contact pressure for as-built and flooded conditions of each soil. An example of the plots is shown for soil T-3 (Thailand) in fig. 5. Data were obtained for each of the three wheel loads on samples of the soil prepared at seven different moisture contents. The only values plotted were those at 540 deg of revolution of the wheel for the flooded condition and 180 and 540 deg for the as-built condition. The regression lines for the as-built and flooded conditions of the soil, as well as those for the other soils, are highly significant. This test, in contrast to other strength tests (cone index, unconfined compressive strength, CBR, and sheargraph), revealed that the moisture content of the soil was not uniquely related to the strength parameter. The range and mean angle of traction and adhesion values for as-built and flooded conditions of temperate and tropical soils were as follows:

	As-Built Condition				Flooded Condition			
	Angle of Traction α_f, deg		Adhesion a psi		Angle of Traction α'_f, deg		Adhesion a' psi	
Soils	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Temperate	30-51	36	0-2.3	1.1	4-29	17	0-1.1	0.4
Tropical	28-44	37	0-2.4	1.1	5-34	18	0-0.7	0.3

Comparison of the data for each parameter shows similarity in the range of values and means for soils of the two climates. The equation, correlation coefficient, and standard deviation from the regression for relations between plasticity index (PI) and angle of traction and adhesion are as follows:

α_f versus PI, not significant at the 20% level

$$\alpha_f' = -0.204\ (PI) + 23.03;\ r = -0.414^{*};\ Sy \cdot x = \pm 7.56\ \text{deg}$$

$$a = 0.025\ (PI) + 0.40;\ r = 0.599^{**};\ Sy \cdot x = \pm 0.56\ \text{psi}$$

$$a' = 0.005\ (PI) + 0.17;\ r = 0.297^{*};\ Sy \cdot x = \pm 0.28\ \text{psi}$$

In each relation, the scatter and trend of data for temperate soils were similar to those for tropical soils, indicating that the relation applied equally to both kinds of soils.

Sheargraph test

Measurements from the Cohron sheargraph[2] test included ultimate angle of friction and cohesion for soil-to-soil failures, and ultimate angle of friction and adhesion for rubber-to-soil failures for as-built and flooded conditions of the soils. An example of the relations for each of these parameters and moisture content for the as-built condition of the soil is shown for soil T-3 in fig. 6. Each point represents an average of data from two tests. The correlation lines shown are visual lines of best fit for the data. In the soil-to-soil and rubber-to-soil shear relations, the angle of friction increased linearly with a decrease in moisture content. The distinctive trend and the narrowness of the scatter band of data for each test indicate a highly significant relation. A comparison of the lines representing the relations for the two types of shear tests shows that the angle of friction increased at a greater rate for the soil-to-soil shear test. The angles of friction were about equal at approximately 35 percent moisture content for the two conditions, so for soil-to-soil shear tests the angles of friction were higher at the low moisture contents and lower at the high moisture contents than for rubber-to-soil shear tests. The departure of points from one line drawn for the cohesion or adhesion versus moisture content relation is greater than it is for the angle of friction versus moisture content relation; however, all indications (from these relations and those for the other soils) are that the cu e of best fit is generally of the shape drawn. Values of cohesion were al ut twice those of adhesion at comparable moisture contents, and peak v ues of cohesion and adhesion occurred at about the same moisture conter The moisture content at maximum cohesion (and adhesion) was severa percentage points greater than the optimum for maximum density. The c elation lines for the other soils tend to have the same trend as thos the example (inverted V for cohesion and adhesion and inverse linea or angle of friction), but the slope and intercept of lines within each of relations are different. Differences between soils of one climate e of the same magnitude as differences between soils of the two clim s, suggesting that the differences were not between the temperate and tropical soils per se.

<u>Drain direct shear test</u>

rained direct shear tests were conducted on soil specimens cut from a mo sample that had been compacted at approximately optimum moisture conte . Shear strength was measured for various normal stresses for each soil, nd the angle of internal friction and cohesion were determined from these lata. Relations between shear strength and normal stress for soils group l by parent materials showed that the slopes and intercepts of the regre sion lines for the temperate soils were not appreciably different from those for the tropical soils. The regression equation, correlation coefficient, and standard deviation from the regression for the relation between angle of internal friction (Φ_d) and plasticity index (PI) are as follows:

$$\Phi_d = -0.17 \text{ (PI)} + 28.68; \; r = -0.544^{**}; \; Sy \cdot x = \pm 4.45 \text{ deg}$$

The trend and scatter of data were similar for temperate and tropical soi , indicating no differences in relations for soils from the two climat . A correlation between cohesion and plasticity index was not signifi ant at the 20 percent level. A comparison of mean values of angle of internal friction (24 and 23 deg) and cohesion (2.8 and 3.0 psi) for temperate and tropical soils, respectively, also shows no appreciable differences.

Consolidation test

The consolidation test, like the drained direct shear test, was conducted on a specimen of soil cut from the mold sample that had been prepared at optimum moisture content. The test provided data for constructing a void ratio-pressure curve for each soil. A comparison of the shapes of curves for temperate soils and tropical soils showed no distinct characteristics that could be used to distinguish soils of one climate from those of the other. The compression index, C_c (a measure of soil compressibility) and the expansion index, C_e (a measure of soil decompressibility or volume increase due to the removal of pressure), were related to the liquid limit (LL) and plasticity index (PI) of the soil. The equation, correlation coefficient, and standard deviation from the regression for each relation are as follows:

$$C_c = 0.0043\ (LL) + 0.01;\ r = 0.864^{**};\ Sy \cdot x = \pm 0.058$$

$$C_c = 0.0035\ (PI) + 0.18;\ r = 0.516^{**};\ Sy \cdot x = \pm 0.099$$

$$C_e = 0.0009\ (LL) - 0.0186;\ r = 0.675^{**};\ Sy \cdot x = \pm 0.024$$

$$C_e = 0.0015\ (PI) - 0.0037;\ r = 0.767^{**};\ Sy \cdot x = \pm 0.030$$

In each relation, the points representing temperate and tropical soil data are scattered equally above and below the regression line indicating that there is no difference in relations for soils of the two climates. A comparison of mean values for temperate and tropical soils of compression index (0.29 and 0.27) and expansion index (0.03 and 0.04) also shows no appreciable differences.

Permeability test

The permeability test was performed in conjunction with the consolidation test under falling-head conditions. The coefficients of permeability for all soils ranged from 3×10^{-9} to 250×10^{-9} cm/sec, except for one soil that had a much higher permeability than the range stated. A comparison of the mean values for temperate and tropical soils under loads of 1, 2, 4, and 8 tons/sq ft showed consistently higher void ratios and coefficients of permeability about twice as great for the tropical soils as for the temperate soils.

Activity ratio

The activity ratios (ratio of plasticity index to the percentage by weight of material finer than 0.002 mm) of all soils, except two, were normal (0.75 to 1.25 activity) or inactive (less than 0.75 activity). The two excepted soils, one temperate and one tropical, were classed as active (greater than 1.25 activity). The temperate and tropical soil data were interspersed throughout the range of activity, with no apparent grouping of soils from either climate.

Effects of drying and rewetting on soil properties

Tests were conducted on dried and rewetted soils to determine the magnitude of change in the Atterberg limits and textural properties due to drying. The results of Atterberg limits tests on dried and rewetted samples of four temperate and four tropical soils from three different parent materials are shown in fig. 7. The data show that the limits decreased as a result of drying and that the amount of decrease was greater for some soils than for others. The rewetted samples generally showed a slight increase in liquid limit relative to the data from the oven-dried samples after four days of soaking, and either a further slight increase or no change after a longer period of soaking. Complete or almost complete reversibility of liquid limit to that existing at the natural condition was indicated for those soils in which the total decrease in liquid limit upon drying was small (about 8 or less). The data show both large and small changes in limits during the drying cycle for soils of the same parent material and for soils of the same climate, suggesting that the degree of reversibility is not affected by those variables. The relation between liquid limit of the natural soil sample (LL_n) and the decrease in the liquid limit upon drying (ΔLL) is shown in fig. 8. The plot shows that the change in liquid limit of the soil upon drying is strongly related to the liquid limit of the undried soil. The points for temperate and tropical soils are equally dispersed above and below the regression line, indicating no difference in relations for soils of the two climates. The effects of drying, therefore, apply equally to temperate and tropical soils.

Mechanical analysis tests were conducted on natural and oven-dried samples of each soil to determine the grain-size distribution. The mean differences between grain sizes of natural and oven-dried samples for temperate and tropical soils, listed according to the U. S. Department of Agriculture (USDA) textural classification and the Unified Soil Classification System (USCS), are as follows:

	Mean Difference, in % Dry Weight				
	USDA Sizes			USCS Sizes	
Soils	Sand	Silt	Clay	Sand	Fines
Temperate	0.3	1.9	-2.2	-0.2	0.2
Tropical	0.7	2.4	-3.1	-0.1	0.1

The minus sign indicates a loss in percentage of grains of the indicated size upon drying. The data show that drying causes changes in the apparent size distribution. Clay particles generally tend to aggregate and form larger sizes. For some soils the reverse apparently is true, i.e. the larger sizes break down into clay-sized particles. The change in particle size is greater for the tropical soils; temperate soils average 2.2 percent and tropical soils 3.1 percent less clay sizes for the oven-dried condition. The data also show for temperate and tropical soils an average small increase in percentage of USDA sand sizes upon drying.

Conclusions

Temperate and tropical soils of similar Atterberg limits and parent materials generally have other engineering properties that are similar and behave similarly when subjected to standard and special engineering laboratory tests. Differences in properties between temperate and tropical soils that cannot be explained in terms of the Atterberg limits are as follows:

a. Residual soils from tropical climates have higher specific gravities.

b. Residual soils from tropical climates have higher percentages of organic matter.

c. Soils from tropical climates that have been compacted in the laboratory to field density and tested at 0- and 0.06-atmosphere tension generally have higher moisture contents and percent saturations and lower densities.

d. In permeability tests of compacted soils in the laboratory, the soils from tropical climates generally have higher void ratios and coefficients of permeability.

e. The increase in particle size upon drying is greater for soils from tropical climates.

The horizontal variations of soil properties (cone index, remolding index, rating cone index, moisture content, dry density, liquid limit, plastic limit, and plasticity index) at a site are similar for soils from temperate and tropical climates.

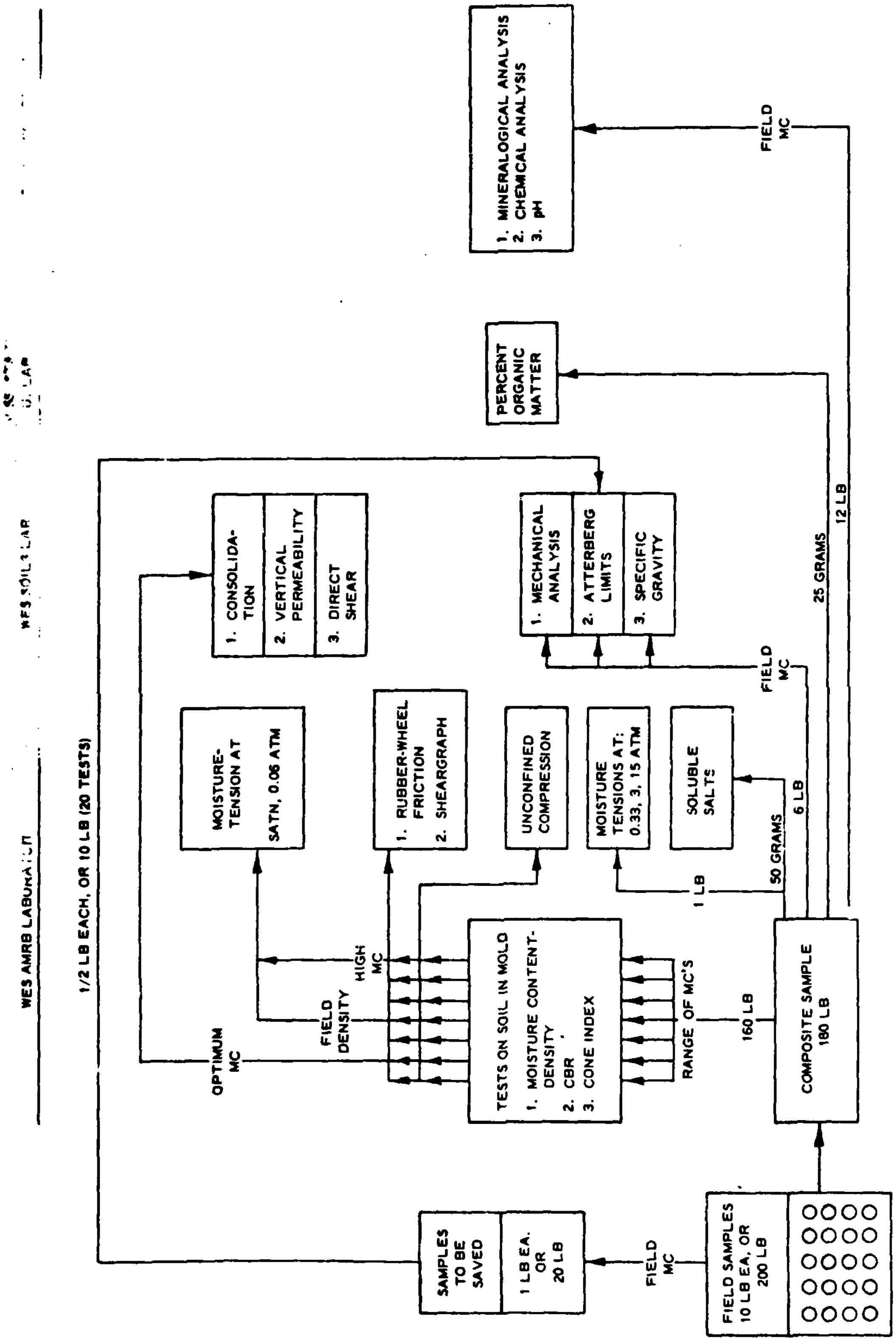
Acknowledgment

This paper was prepared under the guidance and sponsorship of the Directorate of Research and Development, U. S. Army Materiel Command.

References

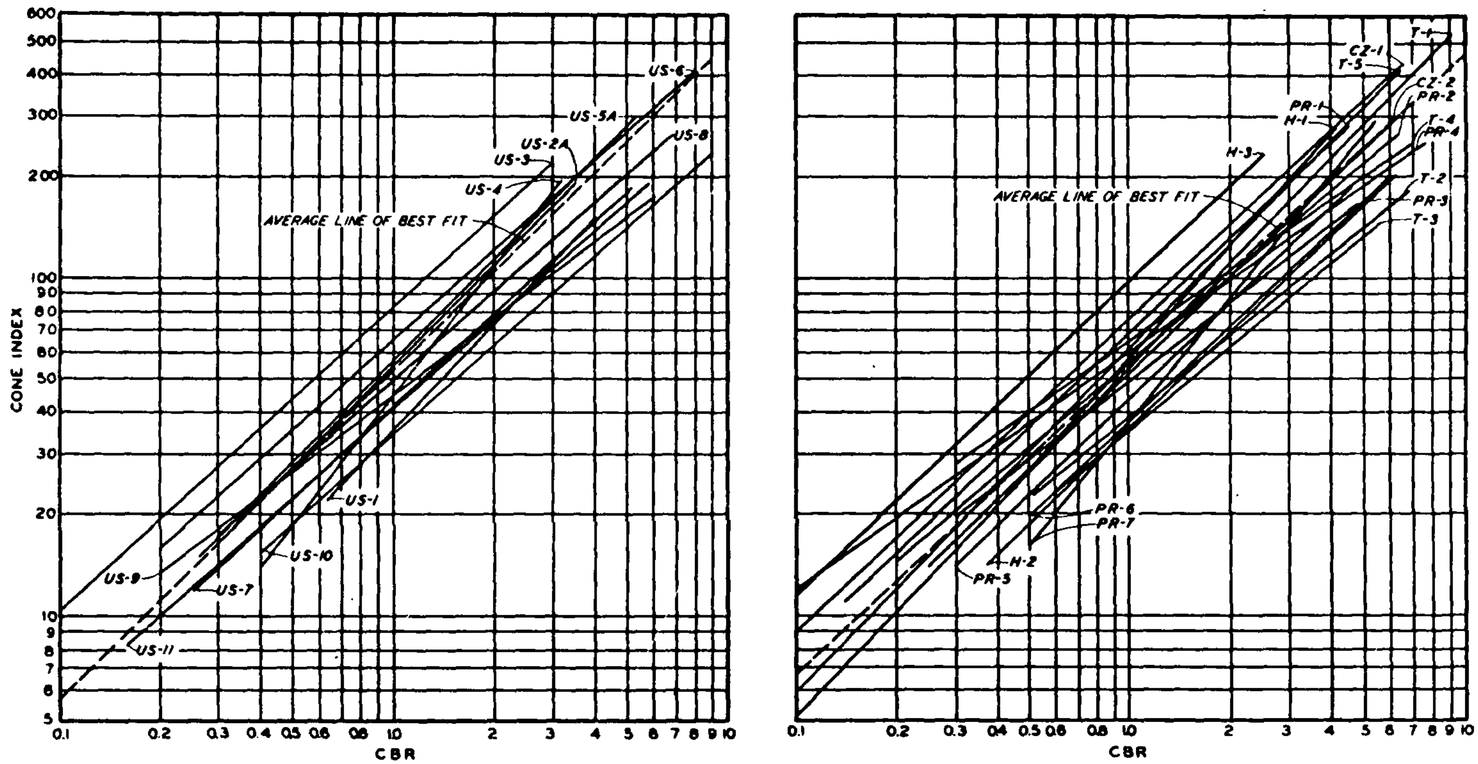
1. U. S. Army Engineer Waterways Experiment Station, CE, Comparison of Engineering Properties of Selected Temperate and Tropical Surface Soils. Technical Report No. 3-732, Vicksburg, Miss., June 1966.

2. Cohron, Gerald T., "Soil sheargraph." Agricultural Engineering, vol 44 (October 1963), pp 554-556.



WES AMRB LABORATORY
WES SOILS LAB
1/2 LB EACH, OR 10 LB (20 TESTS)
FIELD SAMPLES 10 LB EA, OR 200 LB
FIELD MC
SAMPLES TO BE SAVED
1 LB EA. OR 20 LB
COMPOSITE SAMPLE 160 LB
160 LB
RANGE OF MC'S
TESTS ON SOIL IN MOLD
1. MOISTURE CONTENT-DENSITY
2. CBR
3. CONE INDEX
OPTIMUM MC
FIELD DENSITY
HIGH MC
MOISTURE-TENSION AT SATN, 0.06 ATM
1. RUBBER-WHEEL FRICTION
2. SHEARGRAPH
UNCONFINED COMPRESSION
1 LB
MOISTURE TENSIONS AT: 0.33, 3, 15 ATM
50 GRAMS
SOLUBLE SALTS
6 LB
1. CONSOLIDATION
2. VERTICAL PERMEABILITY
3. DIRECT SHEAR
FIELD MC
1. MECHANICAL ANALYSIS
2. ATTERBERG LIMITS
3. SPECIFIC GRAVITY
25 GRAMS
PERCENT ORGANIC MATTER
12 LB
FIELD MC
1. MINERALOGICAL ANALYSIS
2. CHEMICAL ANALYSIS
3. pH

Fig. 1

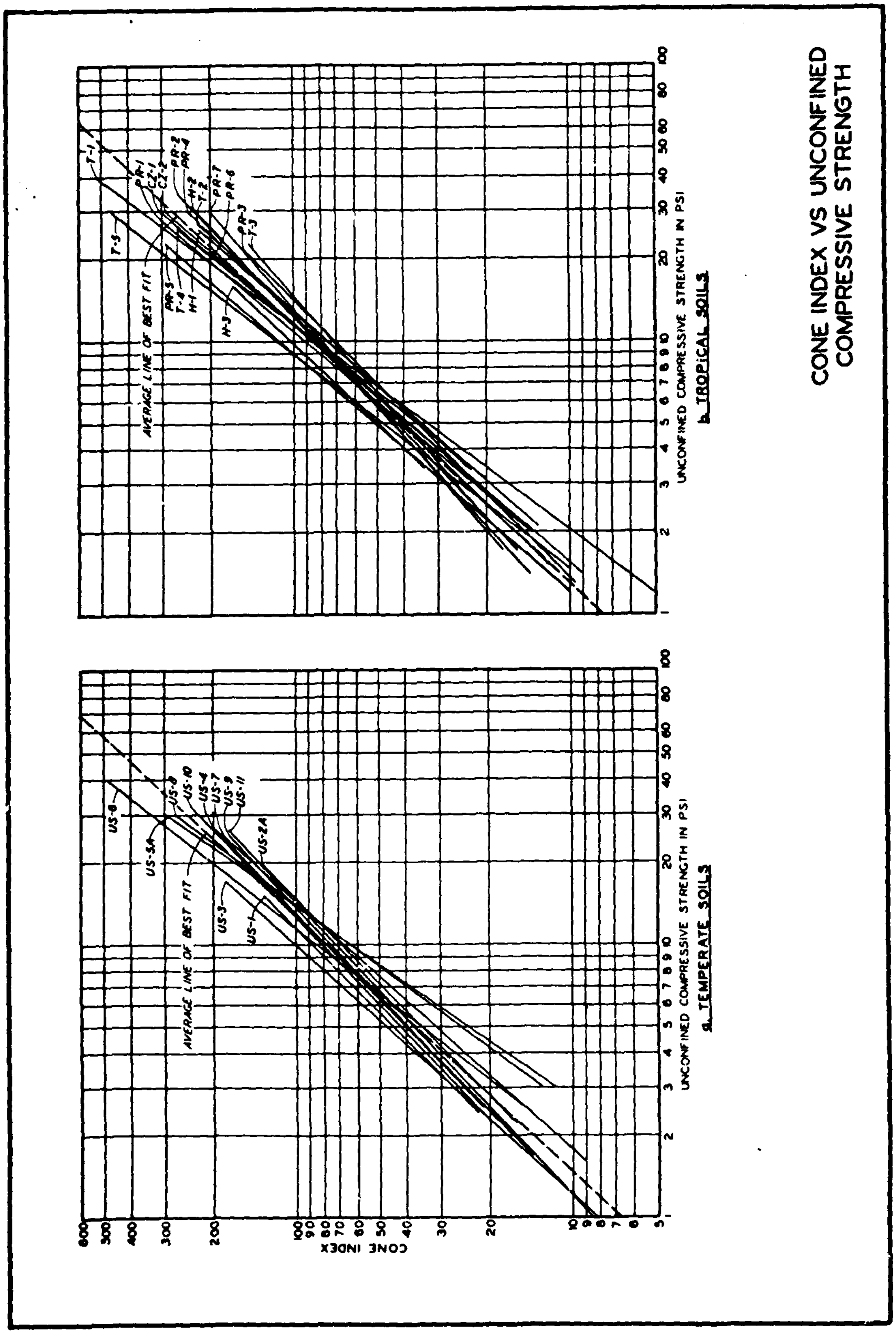


a. TEMPERATE SOILS

b. TROPICAL SOILS

CONE INDEX VS CBR

Fig. 2



CONE INDEX VS UNCONFINED COMPRESSIVE STRENGTH
a. TEMPERATE SOILS
b. TROPICAL SOILS
UNCONFINED COMPRESSIVE STRENGTH IN PSI
CONE INDEX
AVERAGE LINE OF BEST FIT
US-1
US-2A
US-3
US-4
US-5A
US-6
US-7
US-8
US-9
US-10
US-11
T-1
T-2
T-3
T-4
T-5
PR-1
PR-2
PR-3
PR-4
PR-5
PR-6
PR-7
CZ-1
CZ-2
H-1
H-2
H-3

Fig. 3

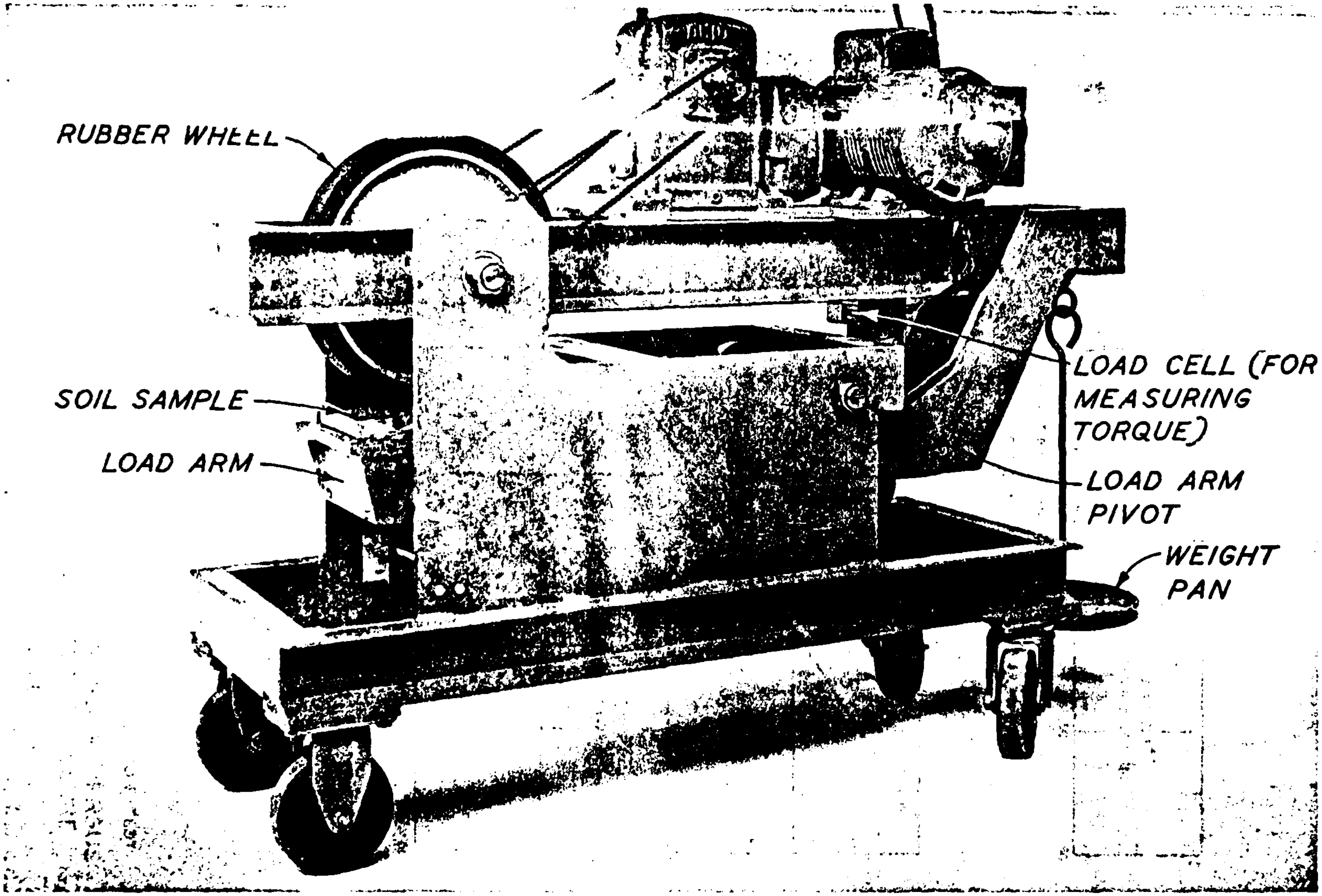
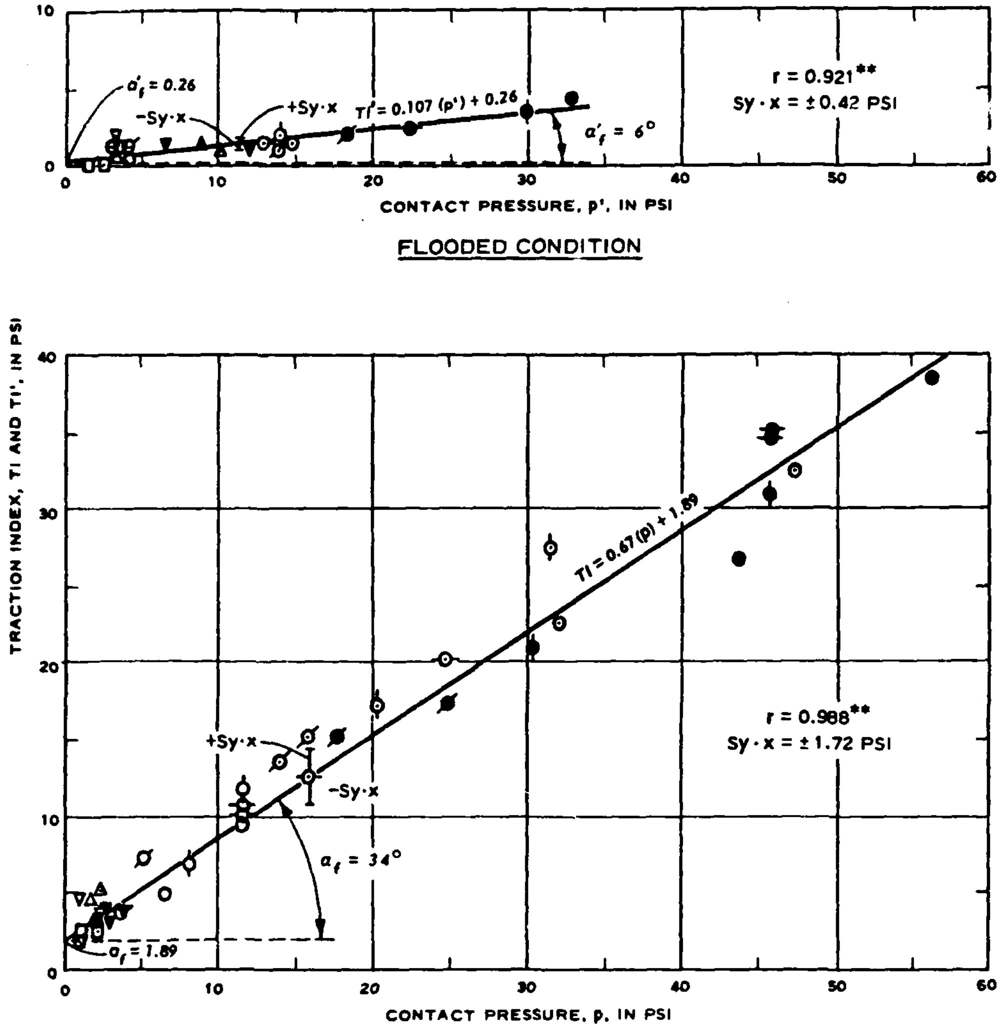


Fig. 4. Friction test machine



AS-BUILT CONDITION

LEGEND

M.C. %	TEST NO.	LOAD IN LB 5	20	35
25.7	6	○	⊙	●
26.5	7	-○-	-⊙-	-●-
29.9	1	○	⊙	●
30.2	5	ø	ø	ø
35.4	2	△	▲	▲
36.2	3	▽	▼	▼
41.6	4	□	⊡	■

** SIGNIFICANT AT 1% LEVEL

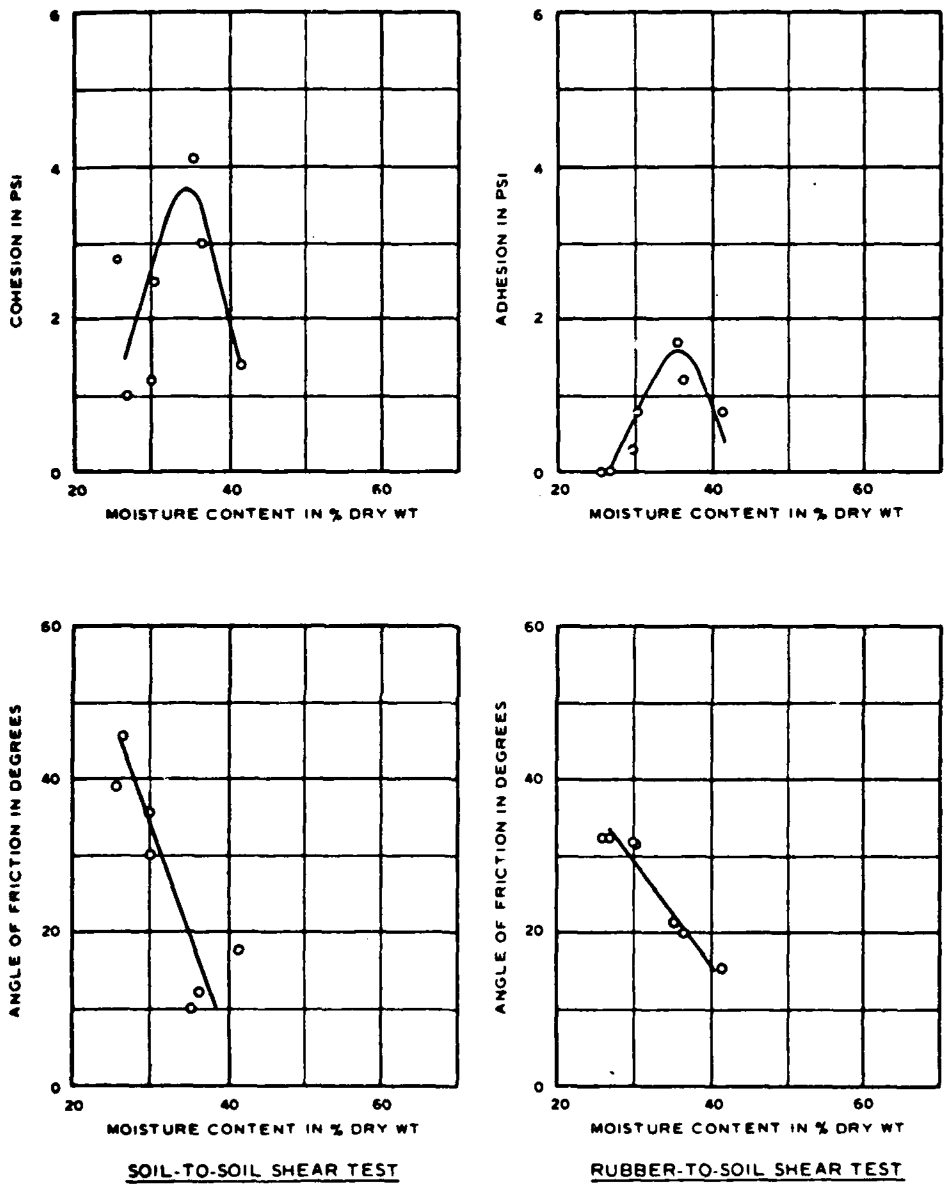
NOTE: DATA FOR AS-BUILT CONDITION ARE FOR 180° AND 540° OF REVOLUTION; THOSE FOR FLOODED CONDITION ARE FOR 540° ONLY.

RUBBER-WHEEL FRICTION TEST

TRACTION INDEX VERSUS CONTACT PRESSURE

SOIL T-3

Fig. 5



LEGEND

o DATA POINT, AVERAGE OF TWO TESTS

—— VISUAL LINE OF BEST FIT FOR DATA POINTS

NOTE: DATA ARE FOR AS-BUILT CONDITION.

SHEARGRAPH TEST

MOISTURE CONTENT VS ANGLE OF FRICTION, COHESION, AND ADHESION

SOIL T-3

Fig. 6

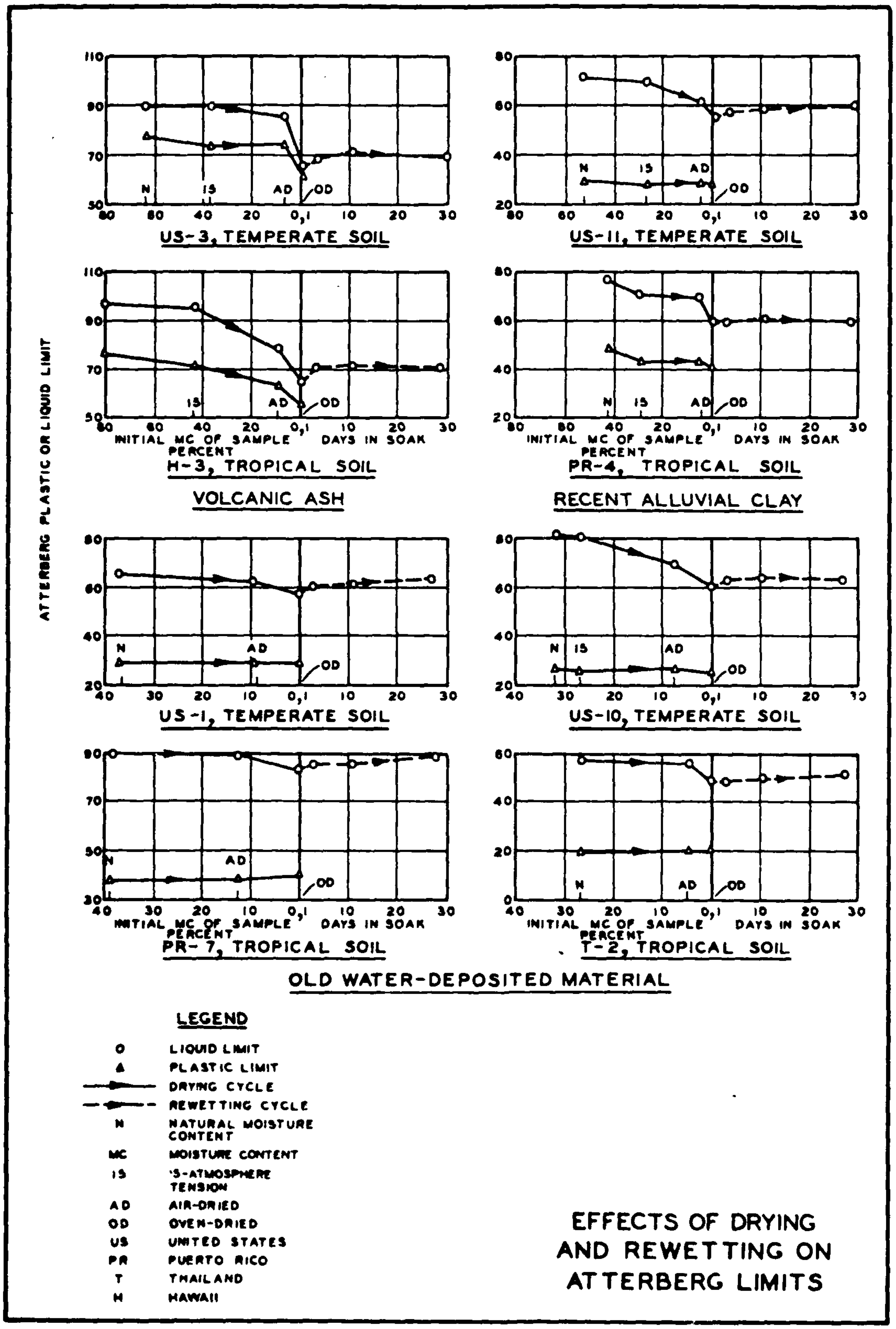
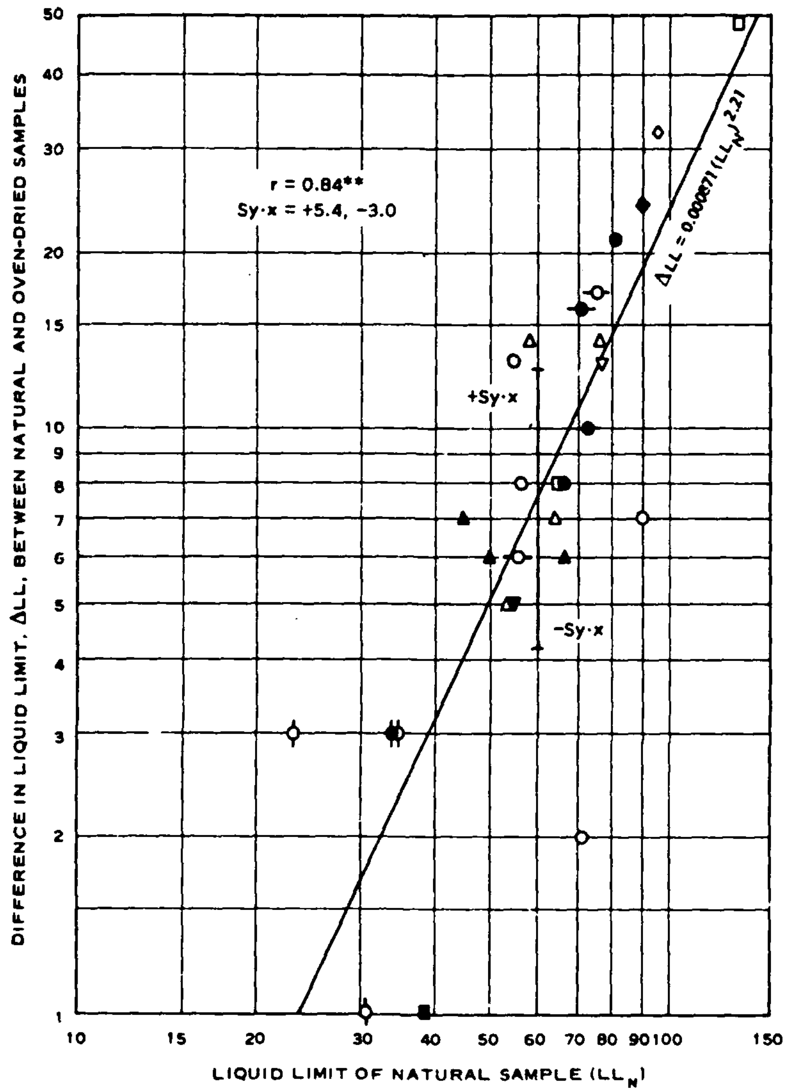

ATTERBERG PLASTIC OR LIQUID LIMIT
US-3, TEMPERATE SOIL
US-11, TEMPERATE SOIL
INITIAL MC OF SAMPLE PERCENT
DAYS IN SOAK
H-3, TROPICAL SOIL
PR-4, TROPICAL SOIL
VOLCANIC ASH
RECENT ALLUVIAL CLAY
US-1, TEMPERATE SOIL
US-10, TEMPERATE SOIL
PR-7, TROPICAL SOIL
T-2, TROPICAL SOIL
OLD WATER-DEPOSITED MATERIAL
N
15
AD
OD
LEGEND
O LIQUID LIMIT
Δ PLASTIC LIMIT
DRYING CYCLE
REWETTING CYCLE
N NATURAL MOISTURE CONTENT
MC MOISTURE CONTENT
15 15-ATMOSPHERE TENSION
AD AIR-DRIED
OD OVEN-DRIED
US UNITED STATES
PR PUERTO RICO
T THAILAND
H HAWAII
EFFECTS OF DRYING AND REWETTING ON ATTERBERG LIMITS

Fig. 7



LEGEND

TEMPERATE SOIL	TROPICAL SOIL	PARENT MATERIAL
▲	△	BASIC IGNEOUS ROCK
▼	▽	ACIDIC IGNEOUS ROCK
◆	◇	VOLCANIC ASH
■	□	LIMESTONE
●	○	OLD WATER-DEPOSITED MATERIAL
-●-	-○-	RECENT ALLUVIAL CLAY
⧫	○	RECENT ALLUVIAL SILT

** SIGNIFICANT AT THE 1% LEVEL

EFFECT OF MOISTURE CONTENT LEVEL ON LIQUID LIMIT

Fig. 8

Table 1

Location, Parent Material, and Properties of Soil

6- to 12-in. Layer

Soil No.*	Location	Parent Material	Texture by Weight, %: Gravel** > 4.76 mm	Sand 4.76 to 0.074 mm	Fines < 0.074 mm	Atterberg Limits: LL	PL	PI	USCS Type	Specific Gravity G_s	Organic Matter Content %	pH	Soluble Salts EC_{25}† millimho/cm	Color††	Hue, Value and Chroma††
									Temperate Soils						
US-1	Corvallis, Oreg.	Old water-deposited material	0.7	15	85	66	30	36	CH	2.70	3.67	5.66	0.69	Pale to dark yellowish brown	10YR 6/2 - 10YR 4/2
US-2A	Shaw, Oreg.	Basic igneous rock	0.2	11	89	45	27	18	ML	2.79	3.10	5.48	0.19	Moderate brown	5YR 4/4
US-3	Tillamook, Oreg.	Volcanic ash	2.8	24	76	89	77	12	MH	2.42	16.91	4.61	1.83	Dark yellowish brown	10YR 4/2
US-4	Pomaria, S. C.	Acidic igneous rock	1.5	32	68	55	29	26	CH	2.67	0.59	5.20	0.22	Moderate reddish to light brown	10R 6/6 - 5YR 5/6
US-5A	Salisbury, N. C.	Basic igneous rock	0.3	30	70	50	28	22	CH	2.72	1.05	6.30	0.20	Light brown	5YR 5/6
US-6	Clayton, Ga.	Basic igneous rock	5.0	25	75	67	49	18	MH	2.72	0.95	5.35	0.16	Light brown to dark yellowish orange	5YR 5/6 - 10YR 6/6
US-7	Oxford, Ala.	Limestone	1.3	21	79	39	22	17	CL	2.71	1.14	5.31	0.30	Light brownish gray	5YR 6/1
US-8	Vicksburg, Miss.	Recent alluvial silt	0	20	80	34	22	12	CL	2.66	0.88	5.29	0.61	Pale yellowish brown	10YR 6/2
US-9	Vicksburg, Miss.	Recent alluvial clay	0	0	100	73	31	42	CH	2.65	1.53	6.38	0.63	Pale yellowish brown	10YR 6/2
US-10	Laurel, Miss.	Old water-deposited material	0	13	87	81	27	54	CH	2.63	1.14	4.72	0.29	Yellowish gray to grayish orange	5Y 7/2 - 10YR 7/4
US-11	Vicksburg, Miss.	Recent alluvial clay	[illegible]	0	100	71	30	41	CH	2.50	2.43	7.34	1.22	Pale yellowish brown	10YR 6/2
									Tropical Soils						
PR-1	Mayaguez	Basic igneous rock	2.5	21	79	58	38	20	MH	3.10	4.78	6.31	0.44	Light brown	5YR 5/6
PR-2	Yobucca	Acidic igneous rock	1.2	29	71	77	39	38	MH	2.65	1.53	4.62	0.15	Dark yellowish orange	10YR 6/6
PR-3	Roosevelt Rds	Old water-deposited material	0	17	83	55	28	27	CH	2.70	2.21	5.69	0.16	Dark to moderate yellowish orange	10YR 6/6 - 10YR 5/4
PR-4	Barceloneta	Recent alluvial clay	0	0	100	76	48	28	MH	2.67	3.55	6.36	1.77	Grayish orange	10YR 7/4
PR-5	Ramey	Limestone	0.7	1	99	65	34	31	MH	2.82	3.69	6.37	0.16	Light brown	5YR 5/6
PR-6	Coroza1	Limestone	0	13	87	130	48	82	CH	2.68	3.34	6.33	0.48	Moderate yellowish brown	10YR 5/4
PR-7	Guanica	Old water-deposited material	0.7	6	94	90	38	52	CH	2.66	3.21	6.45	1.25	Light brownish gray	5YR 6/1
CZ-1	Fort Kobbe	Recent alluvial silt	3.3	25	75	34	25	9	CL	2.67	1.34	5.59	0.22	Moderate to dark yellowish brown	10YR 4/2 - 10YR 5/4
CZ-2	Pedro Miguel	Basic igneous rock	10.7	16	84	76	44	32	MH	2.76	2.57	5.45	0.43	Light brown	5YR 5/6
H-1	Wahiawa, Oahu	Basic igneous rock	0.3	15	85	64	46	18	MH	2.82	2.72	5.32	0.55	Moderate brown	5YR 4/4
H-2	Wahiawa, Oahu	Old water-deposited material	2.5	6	94	71	33	38	CH	2.82	1.09	7.53	1.35	Dark yellowish brown	10YR 4/2
H-3	Waimaka	Volcanic ash	0	24	76	96	76	20	MH	2.85	11.09	5.21	1.14	Moderate yellowish brown	10YR 5/4
T-1	Chantiburi	Basic igneous rock	0.3	21	79	53	42	11	MH	2.88	3.72	5.52	0.26	Moderate brown	5YR 4/4
T-2	Lop Buri	Old water-deposited material	0.1	19	81	56	19	37	CH	2.70	1.78	6.90	0.15	Pale yellowish brown	10YR 6/2
T-3	Bang Khen	Recent alluvial clay	0	1	99	56	24	32	CH	2.68	1.50	6.55	2.46	Pale yellowish brown	10YR 6/2
T-4	Chieng Mai	Recent alluvial silt	0.5	26	74	31	22	9	CL	2.64	1.72	6.75	0.12	Pale yellowish brown	10YR 6/2
T-5	Khon Kaen	Recent alluvial silt	0	49	51	23	15	8	CL	2.64	0.98	5.30	0.95	Pale yellowish brown	10YR 6/2

* US, United States; PR, Puerto Rico; CZ, Canal Zone; H, Hawaii; T, Thailand.
** Removed from composite sample prior to testing.
† Electrical conductivity at 25°C.
†† Determined on oven-dried material finer than No. 325 sieve (0.044 mm) using the Rock-Color Chart provided by the Natural Research Council.

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US-4	Pomaria, S. C.	Acidic igneous rock	1.5	32	68	55	29	26	CH	2.67	0.59	5.20	0.22	Moderate reddish to light brown	10R 6/6 - 5YR 5/6
US-5A	Salisbury, N. C.	Basic igneous rock	0.3	30	70	50	28	22	CH	2.72	1.05	6.30	0.20	Light brown	5YR 5/6
US-6	Clayton, Ga.	Basic igneous rock	5.0	25	75	67	49	18	MH	2.72	0.95	5.35	0.16	Light brown to dark yellowish orange	5YR [illegible]/6 - 10YR 6/6
US-7	Oxford, Ala.	Limestone	1.3	[illegible]	79	39	22	17	CL	2.71	1.14	5.31	0.30	Light brownish gray	5YR 6/1
US-8	Vicksburg, Miss.	Recent alluvial silt	0	20	80	34	22	12	CL	2.66	0.88	5.29	0.61	Pale yellowish brown	10YR 6/2
US-9	Vicksburg, Miss.	Recent alluvial clay	0	0	100	73	31	42	CH	2.65	1.53	6.38	0.63	Pale yellowish brown	10YR 6/2
US-10	Laurel, Miss.	Old water-deposited material	0	13	87	81	27	54	CH	2.63	1.14	4.72	0.29	Yellowish gray to grayish orange	5Y 7/2 - 10YR 7/4
US-11	Vicksburg, Miss.	Recent alluvial clay	0	0	100	71	30	41	CH	2.50	2.43	7.34	1.22	Pale yellowish brown	10YR 6/2
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PR-3	Roosevelt Rds	Old water-deposited material	0	17	83	55	28	27	CH	2.70	2.21	5.69	0.16	Dark to moderate yellowish orange	10YR 6/6 - 10YR 5/4
PR-4	Barceloneta	Recent alluvial clay	0	0	100	76	48	28	MH	2.67	3.55	6.36	1.77	Grayish orange	10YR 7/4
PR-5	Ramey	Limestone	0.7	1	99	65	34	31	MH	2.82	3.69	6.33	0.16	Light brown	5YR 5/6
PR-6	Corozal	Limestone	0	13	87	130	48	82	CH	2.68	3.34	6.33	0.48	Moderate yellowish brown	10YR 5/4
PR-7	Guanica	Old water-deposited material	0.7	6	94	90	38	52	CH	2.66	3.21	6.45	1.25	Light brownish gray	5YR 6/1
CZ-1	Fort Kobbe	Recent alluvial silt	3.3	25	75	34	25	9	CL	2.67	1.34	5.59	0.22	Moderate to dark yellowish brown	10YR 4/2 - 10YR 5/4
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H-1	Wahiawa, Oahu	Basic igneous rock	0.3	15	85	64	46	18	MH	2.82	2.72	5.32	0.55	Moderate brown	5YR 4/4
H-2	Wahiawa, Oahu	Old water-deposited material	2.5	6	94	71	33	38	CH	2.82	1.09	7.53	1.35	Dark yellowish brown	10YR 4/2
H-3	Wainaku	Volcanic ash	0	24	76	96	76	20	MH	2.85	11.09	5.21	1.14	Moderate yellowish brown	10YR 5/4
T-1	Chantiburi	Basic igneous rock	0.3	21	79	53	42	11	MH	2.88	3.72	5.52	0.26	Moderate brown	5YR 4/4
T-2	Lop Buri	Old water-deposited material	0.1	19	81	56	19	37	CH	2.70	1.78	6.90	0.15	Pale yellowish brown	10YR 6/2
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T-5	Khon Kaen	Recent alluvial silt	0	49	51	23	15	8	CL	2.64	0.98	5.90	0.95	Pale yellowish brown	10YR 6/2

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